UTILITY OF AUTOMATIC LIGHTING DESIGN IN 3-D VIRTUAL TRAINING ENVIRONMENTS

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ABSTRACT

Lighting design plays an important role in interactive 3-D training environments; it influences scene perception, scene understanding, attention, visual search, presence, immersion, and emotional involvement. Although there are several research projects that measured the impact of lighting in 3-D environments, little research focused on the development of new lighting design models to enhance the interactive experience. Current lighting design techniques rely on static manual designs. Since interactive training environments are dynamic and unpredictable, such static designs tend to be inflexible and do not adequately support the interaction. In this paper, I will discuss examples showing problems with current lighting design approaches. In addition, I will discuss ELE, an Expressive Lighting Engine, that automatically adapts the lighting to the interaction while accommodating scenario goals, user perception, attention, immersion, and emotional involvement. I also discuss the implication and the use of ELE in interactive 3-D training environments.

1. INTRODUCTION

Interactive 3-D environments are becoming increasingly important for their demonstrated utility in military training environments (ABCNews, august 21, 2003; Sieberg, November 23, 2001; Stanney, 2002; Swartout et al., 2003; Wired, 2003). The wide deployment of game engines, such as Unreal Tournament technologies, have facilitated and accelerated the development process of such immersive training applications. Even with these tools, however, creating training environments still require much time and effort. In addition, these engines often do not include methods for adapting to or accounting for the user's perceptual and cognitive processes during training. There are several limitations with current tools, especially in their use for training environments. In this paper, I specifically focus on lighting design.

Lighting design plays a very important role in creating immersive 3-D environments. It influences user's perception, scene understanding, attention, visual search process, presence, and emotional involvement. It should be noted that lighting is not the only factor that affects these perceptual and cognitive processes; it is among several visual and audio components that are used for this purpose, including ambient sounds, camera, and textures.

Lighting has been used by many film, theatre, and animation designers to set atmosphere, evoke moods, and heighten the emotional engagement. These qualities are very important for 3-D training environments. Research has shown that in emotionally heightened situations memory retention increases (Ulate, 2002). Thus, the use of lighting to increase emotional engagement can stimulate better memory retention. Lighting has also been used by many designers to provide and retain attention and involvement (Alton, 1995; Birn, 2000; Brazel, 1997; Calahan, 1996). This is specifically important for training environments, since continuous concentration and attention is needed to complete training scenarios and motivate learning.

To develop a lighting design for interactive 3-D environments, current designers predefine the number of lights used for each set, and predefine their positions, angles, and colors depending on the desired atmosphere, the light sources present in the set, the time of day, and the location. This static manual design is inflexible. Physical and scenario configurations of interactive 3-D environments often change unpredictably due to user interaction. Thus, a lighting design that is configured for a particular mood or atmosphere may no longer be valid given the run-time fluctuations of the user's emotional engagement and the situation given user's interaction. Also, a lighting design that is configured for guiding trainees' visual search process inherently does not account for the dynamic change of focus depending on the trainee's performance and scenario goals.

To better facilitate training goals and enhance current training environments, I propose the use of an automatic lighting design technique that adapts the lighting accommodating the interaction and scenario goals as well

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as accounting for lighting design functions, including attention, emotional stimulation, and enhancing scene understanding and perception. In this paper, I discuss an automatic lighting design system, called ELE (Expressive Lighting Engine). In particular, I present results and discuss implications and utility of ELE in training simulations.

2. FACTORS INFLUENCED BY LIGHTING IN 3-D ENVIRONMENTS

2.1 Realistic appearance and Rendering

Many training environments have emphasized realism. Although realism may be important for many training applications, it is not essential for achieving presence, attention, and emotional engagement (Zimmons, 2004). Also, realism is not always in conflict with providing atmosphere or mood, as one may believe. Many film-based techniques have been employed by cinematographers, where subtle changes in contrast and exposure levels are applied to the scene to heighten the audience's emotional experience, while maintaining the perceived realism of the environment portrayed (Block, 2001; Brown, 1996; Viera, 1993). These methods elevate tension, anticipation, and increase attention, emotional engagement, and presence.

Achieving realistic lighting in real-time is still a challenge. Real-time rendering techniques used by many game engines and interactive 3-D environments often approximate the lighting process, e.g. they do not account for refractions or inter-reflections of light (Moller & Haines, 1999). This has forced designers to adopt several tricks to produce more realistic rendering effects, e.g. designers use ambient lights to simulate the reflections of light on the different surfaces (Birn, 2000). Experienced designers use these tricks and carefully balance their use, knowing that too much ambient light tend to flatten the image (Birn, 2000) and no ambient light leads to darker and less realistic scenes.

Global illumination is a term used by the graphics community to refer to the general problem of calculating light propagation in simulated environments, accounting for the many inter-reflections between scene surfaces. It has been shown that such realistic measures are not important for achieving presence, attention, and emotional engagement (Zimmons, 2004). Zimmons conducted several experiments to compare rendering algorithms (local lighting vs. global illumination) and the impact of using a more realistic rendering algorithm on presence (Zimmons, 2004). His results show that global illumination didn't produce significantly better presence than a less realistic illumination algorithm. This concludes that presence and attention can be stimulated without emphasis on realism. Thus, training environments that strives for ensuring presence or emotional engagement do not necessarily need realistic rendering.

2.2 Scene Perception and Understanding

Since lighting affects scene rendering, it inherently affects users' perception and scene understanding. This is especially important for fast paced environments, where the scenario depends on the quickness of the trainee in deciphering the environment and responding. To achieve better scene understanding and perception, lighting designers identified several goals for their designs. These goals include: achieving good visibility of important areas and landmarks, provide a sense of visual depth or depth of field, direct viewer's attention to important areas, and configure lights to match the local light sources present, e.g. torches or sunlight through a window (Brown, 1996; Millerson, 1991). Designing scene lighting to satisfy these goals is important to achieve better scene perception and understanding for interactive environments with complex elaborate scenes.

2.3 Presence

Presence is the sense of being teleported into a virtual space (Freeman, Ijsselsteijn, & Lessiter, 2000; Riva, Davide, & Ijsselsteijn, 2003; Singer & Witmer, 1999). Many elements affect presence, e.g. ambient sound. Lighting has a significant impact in simulating space (Alton, 1995; Calahan, 1996; Carson, 2000). Lighting designers identified two goals that have direct effect on simulating space: (1) the use of local light sources present in the scene to guide the process of configuring light positions, angles, and color, and (2) the setting of the lighting atmosphere by choosing and balancing colors of light to set a particular time of day, and feel for the environment (Alton, 1995; Block, 2001; Brown, 1996; Calahan, 1996; Gillette, 1998; Millerson, 1991; Palmer, 1985).

2.4 Emotional Involvement

Lighting designers have identified mood and emotions as one of the main functions or requirements of a lighting design. They modulate the lighting color contrast and affinity in terms of saturation, brightness, and warmth/cool colors during the scene and between scenes to increase tension and support the scenario goals (Block 2001). This intensifies the action and heightens the scene presented, which in turn increases the emotional involvement. It should be noted that cinematographers often use visual patterns integrating camera, lighting, and character actions together to heighten the emotional engagement (Alton, 1995; Block, 2001; Campbell, 1999; Cheshire & Knopf, 1979).

3. LIMITATIONS OF CURRENT TECHNIQUES

Since there are no lighting design models specifically formulated for interactive 3-D environments, current models adopt a cinematic approach. The problem with using a cinematic approach lies in the difference between film and real-time interactive environments. In designing a movie, the designers already know the plot, the actions, the desired or intended emotions and moods, and in some cases, he/she have already seen rehearsals and talked with producers and directors. Interactive 3-D environments, on the other hand, are unpredictable due to user interaction. Hence, design parameters, including character/object locations and importance, are not known at design time. For example, character relationships change depending on user's behaviors and actions, and physical positions of characters change relative to the user. Therefore, designers cannot script camera actions, lighting, and staging to accommodate all situations and perform desired perceptual effects. Thus, current manual designs often results in unwanted or undesirable effects.

In addition, this method forces designers to explore a large space of possible solutions resulting from the combinations of low-level parameters and possible scenarios. While experience can narrow the search space, an experienced lighting designer still requires much time and effort to develop an adequate design. Most often such design, because of its static nature, does not adapt to the unpredictability of interactive environment. Thus, most often the technique leads to static and context-insensitive lighting that does not accommodate variations in scene's spatial configuration, mood, or visual focus. Examples of such problems surface in many interactive productions, such as games and training environments.

3.1 No dynamic adaptation of the design to accommodate interaction

Figure 1 shows a screenshot from a game called *Blade of Darkness* where the designer aimed to stimulate mood by attaching light sources to torches (practical sources[1]) in the scene, and dynamically calculating the lighting accordingly. While this technique produces effective mood, it has several drawbacks. Lighting is solely dependant on practical sources in the scene; there is no method for manipulating the design to achieve other visual design goals such as visual focus, visibility, visual intensity, and mood. Therefore, the design often leads to many inappropriate effects, as illustrated in figure 1. The figure shows insufficiently lit characters or action due to unpredicted movements and the absence of an algorithm that adapts the design to accommodate changes in the environment. In figure 1, the participant (whose back is towards us) is fighting another character (facing us) who is barely visible, and in this case the participant cannot determine if his/her sword touched the other character or not, which frustrates him/her and diminishes his/her engagement. This problem surfaces in many other 3-D applications as well.

Fig. 1. A Screenshot from *Blade of Darkness*

3.2 No dynamic light modulation for tension

Movies and games all use techniques to intensify the dramatic moments in the scene (Alton, 1995; Birn, 2000; Block, 2001; Calahan, 1996; Campbell, 1999; Cheshire & Knopf, 1979; Maattaa, 2002). Currently game designers have developed several strategies to dynamically intensify the experience based on audio, camera movement (Adventure, 2003), texturing, and level design (Carson, 2000; Maattaa, 2002). Most of these methods are inherently tied to the specific game or application the method was developed for, i.e. they are not generic enough to be used by other games or applications.

While cinematographers, animators, and theatre designers use lighting to parallel the tension in the scene and evoke emotions, game designers minimally use lighting for this function. Recently, however, many techniques have surfaced showing the impact of using dynamic lights for establishing and modulating tension, e.g. *Doom 3* (Macek, 2004). This technique is still not adopted in all games due to the design tools and the established production pipeline. As shown by recently adopted designs, dynamic automatic lighting modulation presents a potentially less obtrusive and more subtle but effective solution that has yet to make its way to the production pipeline of interactive 3-D applications.

Dynamic lighting techniques currently used by games, such as *Doom 3*, are still in early development. They currently rely on fixed predefined patterns that designers set and trigger depending on a predefined situation, e.g. before monsters attach or when user enters zone *x*.

[1] Practical sources are sources suggested by the set, such as lanterns, windows, or torches.

3.3 Problems with scene understanding and visual attention

We conducted an experiment to measure visual attention and scene understanding within 3-D environments. We asked several students to play a popular first person shooter game called *Unreal tournament 2003*. We asked them to wear an eye tracker. We recorded their eye movements superimposed on the game video for analysis.

From our observations and taped interaction, we deduced that the number of misses of novice users is significantly higher than that of expert users. These misses have caused naïve users to be killed instantly. One interaction proceeded as follows. A user enters a room, scans the environment for any visible enemies. Even though enemies exist, the user doesn't see them. The user advances into the room, hears gun shots, starts shooting everywhere while scanning the environment again, spotting nothing. The user looks at his health, notices that his health is dropping. He starts scanning the environment again, but by the time he actually sees the enemy, he was dead.

These results are significant for training applications. The results show that in complex 3-D environments naïve users were not able to spot important characters, and thus failed to respond. This shows that the visual search process as well as task performance was influenced by scene composition and lighting (later I will show enhancements of lighting that alleviates this problem).

Many games solve this problem by adding a halo around characters and important objects, as evident in *Unreal Tournament 2004*. While this presents a workable solution, it contradicts with the realistic requirement established for lighting design, and can sometimes be infeasible for applications where object importance change over time.

4. ELE – EXPRESSIVE LIGHTING ENGINE

To alleviate the problems discussed above, I developed a new lighting design model called ELE (Expressive Lighting Engine) that automatically and dynamically adjust the lighting in an interactive scene accommodating the lighting design functions (attention, emotional involvement, depth, and enhancing scene understanding and perception) given the situation and user actions evaluated at run-time. Since ELE has been published elsewhere (Magy Seif El-Nasr & Horswill, 2003; Magy Seif El-Nasr & Horswill, 2004), I will only summarize ELE in this section to give the reader a quick overview of the inner details of ELE. For a more comprehensive treatment of ELE, readers are referred to (Magy Seif El-Nasr & Horswill, 2003; Magy Seif El-Nasr & Horswill, 2004).

Based on the lighting functions or scene factors influenced by lighting discussed above, I identified several lighting design goals, as follows:

- Provide necessary visibility of action
- Maintain illusion of light source (to achieve realism)
- Provide visual focus
- Provide depth
- Evoke emotions
- Set atmosphere
- Maintain visual continuity

ELE is based on cinematic and theatrical lighting design theories (Alton, 1995; Block, 2001; Brown, 1996; Crowther, 1989; Gillette, 1998; Millerson, 1991); it is designed to automatically select the number of lights, their positions, colors, and angles to achieve the goals enumerated above. To accomplish this task, ELE uses lighting design rules represented mathematically in an optimization function. The use of optimization is important to balance conflicting lighting design goals. While adjusting the lighting, ELE maintains visual continuity.

I assume that there exists a system that passes several parameters to ELE, including a set of parameters describing style, local light sources, scene graph, characters' dimensions, dramatic focus (the area/characters to which attention should be directed), current scenario goals, current user actions, and the dramatic intensity of the situation. Using these parameters, ELE computes the number of lights to be used. For each of these lights, it computes the type of instrument (e.g., spot light or point light), color in RGB color space, attenuation, position as a 3D point, orientation including the facing and up vectors, range, masking parameters, and, depending on the light instrument used, the Penumbra and Umbra angles. These parameters are given to a rendering engine to render the frame.

ELE first determines where to direct viewers' attention given the number of characters in the frame and the dramatic importance of their actions. I use the term *dramatic focus* to denote the area where attention should be directed. ELE then dynamically allocates lights to visible areas in the scene. Once lights are allocated to areas, ELE selects angles and colors for each light in the scene, thus forming a light setup. The light setup is then given to the rendering engine to render the frame.

ELE divides the visible area into *n* different areas. It categorizes these areas as: focus, describes the focus of the shot, non-focus, areas surrounding the focus area, and background areas. ELE assigns lights to each area depending on its category. The angle and color systems

assign angles and colors depending on the number of lights assigned to the area and its category.

4.1 Selecting Angles

The angle system selects an angle for each key[2] light according to the lighting design goals. Cinematic rules used to satisfy these goals often contradict with one another. Angles used to establish mood, for example, don't usually produce good visibility, e.g. rim or silhouette angles. Thus, I softened these rules into cost functions, where the designer controls weights associated with the contradicting requirements, such as mood, visibility, and modeling:

$$\begin{aligned}\mathrm{cost}(k,k^{-},m) = \lambda_v V(k) + \lambda_{-}\left|k-k^{-}\right| + \lambda_m\left|k-m\right| + \\ \lambda_l \min_i\left|k-l_i\right|,\end{aligned} \qquad (1.1)$$

where k is the key light angle, k^{-} is the key light angle from the previous frame, and m is the mood angle suggested by the artist, λ_v is the cost of deviation from an orientation of light, which establishes best visibility, λ_{-} is the cost of changing the key light angle over time (to enforce visual continuity), λ_l is the cost of deviation from an established light source angle/direction. In addition, for each light source, and l_i is the angle of light from the light source i on the subject or area in question, and λ_m is the cost of deviation from an angle that shows a specific mood. Based on Millerson's work (Millerson, 1991), I derived the following formula to evaluate visibility and modeling:

$$V(k) = \sin(\left|k-c\right|)\cos(k-s), \qquad (1.2)$$

where k and c are the azimuth angles of the key light and camera relative to the subject and s is the azimuth angle toward which the subject is facing. Millerson recommended an elevation angle between $\pi/6$ and $\pi/3$ (Millerson, 1991).

I used a linear optimization algorithm based on hill climbing to select an angle for each key light that minimizes the cost function above.

Fill and backlight azimuth angles are calculated depending on the value of the key light angle and the angle between the camera and the subject. According to the guidelines described by Millerson (Millerson, 1991), fill light azimuth and elevation angles are calculated to be the mirror image of the key light angle. I derived a formula to compute backlight azimuth angle as follows:

$$b = \left(k-c+\pi\right)\bmod 2\pi, \qquad (1.3)$$

where k and c, again, are the are the respective angles of the key light and camera. Backlight elevation angle is set to $\pi/4$ as recommended by Millerson (Millerson, 1991).

[2] Key light is the main source of light that establishes the direction and the shadows

4.2 Selecting Colors

The interaction between colors assigned for lights lighting each area in a scene composes the contrast and feeling of the entire scene. Thus, I differentiate between the three types of areas: background, focus, and non-focus. I calculate contrast and depth according to the difference between colors assigned to each of these areas.

Using the ideal values for visibility, depth, saturation, warmth, and lightness for each area, and their associated costs, the system uses constrained nonlinear optimization to select a color for each individual light in the scene that will minimize the cost function:

$$\mathrm{cost}(t,c_i,c_{i-1}) = P(t,c_i,c_{i-1}) + \varepsilon\sum_j^{\rho}\log(-g_i(x)), \qquad (1.4)$$

where g: $R^3 \rightarrow [0,1]$ describes the desired color palette. P is defined as follows:

$$P(t,c_i,c_{i-1}) = \begin{aligned}\lambda_s(S(c_i)-s)^2 + \lambda_l(L(c_i)-l)^2 + \\ \lambda_d(D(c_i)-d)^2 + \lambda_w(W(c_i)-w)^2 + \\ \lambda_c(C_\phi(c,c_i)-c_i)^2 + \lambda_{ch}E(c_i,c_{i-1}),\end{aligned} \qquad (1.5)$$

where $S(c_i)$ is saturation, $L(c_i)$ is lightness for color c_i and are all calculated using formulae defined in (Castleman, 1996). $C_\phi(c, c_i)$ denotes contrast of color c_i given c. The values for the costs λ_s, λ_c, λ_w, λ_l, λ_{ch}, λ_c are given by the designer, and λ_s, λ_c, λ_w, λ_l are computed by ELE for every area type (focus, non-focus, and background).

5. IMPLEMENTATION

ELE has been implemented in C#. It is an API library. It sits on top of a rendering engine. It has also been configured to use XML to interact with rendering engines. This allowed the architecture to be more extensible. We have implemented two interfaces for ELE for: wildtangent, a publicly available graphics engine used to develop web-based games, and Unreal 2.0 engine used for developing Unreal Tournament 2003 (*UT2003*) and has also been used to develop other games, e.g. Thief III, and training applications, e.g. leader's project at Institute for Creative Technologies (Gordon, Lent, Valsen, Carpenter, & Jhala, 2004).

One concern was the performance of ELE within a fast paced interactive environment. I found no performance problems when interfaced with UT2003. ELE ran at a 30 frames/second rate, and thus was successfully ported to Unreal platform. There were some other issues concerning the limitation of the unreal rendering engine to render dynamic spot lights, which forced us to use point lights instead.

During the implementation and testing stage, I found several benefits of using ELE over current methods.

Using ELE designers were able to quickly set the lighting design without worrying about low-level details of placements, angles, or color. This expedited the development process. Figure 2 shows three different levels within *UT2003* lit using ELE. This did not require any designer interference, except for initial setting of constraints specifying priorities for the lighting design goals. As shown, figure 2 illustrates different renderings where ELE was configured differently in regards to contrast and overall atmosphere. The upper left image shows a scene where ELE was configured for good visibility, while the lower right image shows a scene where ELE was configured for mood lighting, and thus the character in the lower right scene was backlit. The two right scenes are set for a low-key torch lighting, while the image of the scene in the lower left shows a more cinematic lighting style with shades of green.

Fig. 2. Different Levels lit using ELE

6. RESULTS

6.1 Scene Perception and Task performance

As you can see from the formulas discussed above, ELE finds the best lighting setup (layout, angles, and colors) that provides good visibility for action, and depth depending on set priorities for these goals. Also, as it can be seen by the algorithms used to divide the visible areas in the scene, allocate lights, and set colors, ELE focuses on configuring lights to provide best visual focus (or visual attention) to adequately direct user's attention. The integration of all these methods and goals enhance scene perception and improve users' perception of complex 3-D environments.

To measure this quality, we repeated the eye-tracker experiment described above with the same game (*Unreal Tournament 2003*) and level, but where the lighting was set by ELE rather than set by a lighting designer. We invited 26 subjects to play *Unreal Tournament 2003*. We asked them to wear a baseball cap that has an eye tracker mounted on it. We video taped their interaction. Only 7 of the subjects have played Unreal Tournament before. All subjects have played non first person shooter video games before.

ELE was configured with the following visual design goals priorities: visibility= high, visual focus=high, visual continuity=high, others are all low. Screenshots of two rooms configured by ELE is shown in figure 3.

By qualitatively analyzing the observed and video taped responses, we deduced that naïve users were able to quickly spot the characters and decipher the complex 3-D environment, and thus were able to react in a timely manner. This is a great enhancement compared to the scene rendered without ELE.

This is especially important for training environments where trainees are asked to accomplish a task that involves visual search. By avoiding the visual spotting and complex environment deciphering problem, the designers and developers of training experiences can focus on the actual training scenario.

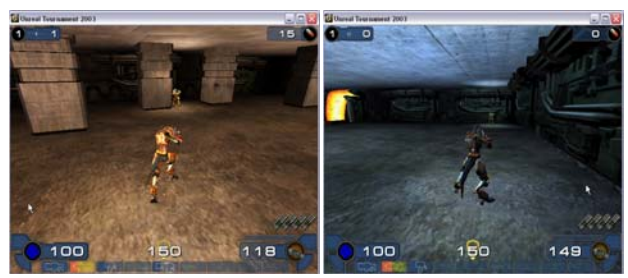

Fig. 3. Visual Focus

6.2 Increasing Emotional Involvement

Emotional engagement has been identified to be of particular significance to training simulations, because of its influence on presence (Freeman et al., 2000; Riva et al., 2003; Singer & Witmer, 1999; Zimmons, 2004) and memory retention (Ulate, 2002). Many game designers use sounds and visual patterns to emphasis dramatic moments in the game and thus escalate tension and increase emotional involvement. For example, designers have used a red blinking screen to signify danger (or health dropping beyond safe levels). In addition, some games designers increase color saturation between missions (*Devil May Cry*). These methods are often obtrusive, and not continuous.

In contrast, ELE provides a continuous technique for increasing tension while balancing other visual properties.

As a testing case, I have configured ELE to increase tension every 2 milliseconds in the game, thus, producing results shown in Figure 4. As shown in the figure, ELE varies the visual tension level portrayed while maintaining visual continuity and general color style of the scene, which is a torch lit scene in this case. I have not yet validated the technique's perceptual effect or interaction impact. However, the technique is comparable to other techniques used in cinematographers and animators (Alton, 1995; Block, 2001; Bucklan, 1998).

Fig. 4. Visual Tension in the Scene

I hypothesize that this approach increases engagement and emotional involvement, as discussed in cinematic theory (Block, 2001; Calahan, 1996; Cheshire & Knopf, 1979) and outlined by psychological theories (Kueller & Mikellides, 1993; Oullette, 2001; Valdez & Mehrabian, 1994). Thus, I argue that this technique can increase emotional involvement and engagement in training simulations, and can have a great impact on memory retention and learning (Ulate, 2002).

7. CONCLUSION

In this paper, I discussed the role of lighting and its impact on interactive 3-D training environments. I identified several factors affected by the lighting design of the environment, including emotional engagement, attention, presence, and scene perception and understanding, which also impacts visual search and task performance. I have discussed several shortcomings of current lighting design techniques in addressing these factors due to the unpredictability of the interactive environment. I then briefly described ELE – a lighting system that automatically adapts lighting to the continually changing situation using rules developed based on cinematic and theatrical lighting design theory, and thus accounts and enhances visual attention, emotional engagement, scene perception and understanding in interactive 3-D environments. The results discussed show great promise for the success of the approach. I also discussed the impact and utility of ELE for interactive 3-D training applications.

This research and the success of the approach trigger many future directions. One direction is to interface the lighting system with several training applications and conduct experiments to evaluate the impact of the lighting model discussed here on memory retention, learning, and task performance. It would also be interesting to evaluate the different configuration of lighting style that can be achieved using ELE and measure their effect on learning and training.

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